FOURTH INTERNATIONAL CONFERENCE ON SCANNING TUNNELING MICROSCOPY/ SPECTROSCOPY (STM '89)

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STM '89 focused on the exploitation of STM and its related technologies. The conference featured sessions on semiconductors, metals, biological molecules, superconductors, electrochemistry, lithography, atomic force microscopy, theory and practice of tunneling tip, new concepts in proximal probe instruments, and practical applications of tunneling tip.

INTRODUCTION

The Fourth International Conference on Scanning Tunneling Microscopy/ Spectroscopy (STM '89) was held in Oarai, Ibaraki, Japan, on 9-14 July 1989. This conference focused on the exploitation of STM and its related technologies (so-called **proximal** probes for their common feature of positioning and moving two surfaces with subnanometer precision). The incredible growth of the conference continued, with the 220 papers this year contrasting with 150 in 1988 and 100 in 1987. Perhaps not surprising was the fourfold growth in the contributions from Japanese investigators. The conference featured sessions on semiconductors, metals, biological molecules, superconductors, electrochemistry, lithography, atomic force microscopy, theory and practice of tunneling tip, new concepts in proximal probe instruments, and practical applications of tunneling tip.

SEMICONDUCTORS

There were three regular sessions and one poster session on semiconductors. This was the largest single topic at the conference since historically the majority of the first STM work focused on semiconductors. The STM images of the various semiconductor surfaces displayed at the conference typically show exceptional atomic resolution due to highly localized charge distributions on semiconductors. The first session was started off by Becker (AT&T Bell Labs), who showed high resolution images of steps and domain boundaries on silicon surfaces and compared them to computer simulations to extract the amount of contraction in the surface layer. Mo (Univ. of Wisconsin-Madison) gave a paper on Si on Si epitaxy where he was able to estimate the Si self-diffusion coefficient of 10^{-13} cm^2/sec. He also showed that with Monte Carlo simulations the shape anisotropies observed in the growth were not due to diffusion anisotropies but from anisotropic interactions.

The second session was led off by Hashizume (Univ. of Tokyo), who gave a paper on alkali metal adsorption on Si surfaces. For Li adsorption, chain formation perpendicular to the Si dimer rows was observed. The chain axes are rotated 90° to what one might intuitively expect, where the atoms would go in an open furrow on the surface, as seen, for example, with the one-dimensional Cs chains on the GaAs(110) surface reported by Stroscio (National Institute of Standards and Technology (NIST), Gaithersburg). Anisotropic surface interaction is used to explain the chain growth on the Si(100) surface and is common to other adsorbates on this surface, as seen with Ga adsorption, reported by Baski (Stanford Univ.) in this session. An interesting paper was given by Wiesendager (Univ. of Basel, Switzerland) on the comparison of atomic force microscopy (AFM) and STM in imaging charge density waves in transition metal dichalcogenides. He found that the charge density waves were absent when using the AFM, while the STM was able to image them. This was surprising since in the repulsive force mode the AFM is also sensitive to the tails of the charge density, similar to the operation of the STM. Dr. Wiesendager proposed that the charge density waves were absent due to the applied force or pressure used in the AFM experiment.

The third session was opened by a very interesting paper by Hamers (IBM Yorktown Heights), who presented results on laser-assisted STM. In this paper Hamers showed that a nonequilibrium population of photogenerated carriers could be detected with tunneling spectroscopy (a similar result was presented for GaAs by Neuman (Univ. of Heidelberg, FRG) in the poster session). The extension that Hamers showed was that the surface photovoltage, which is the amount of band bending change induced by the presence of photogenerated carriers, could be imaged simultaneously with the topographic image using a gated feedback technique. In imaging the surface photovoltage Hamers showed that the two halves of the Si(111) 7x7 have a different photovoltage signal. He also showed that the power spectrum of the photovoltage could be used as a local probe of carrier lifetimes, where he observed higher rates for carrier recombination on defected regions of the surface.

Most of the other semiconductor papers and posters reported on metal-semiconductor and semiconductor-semiconductor systems. GaAs epitaxy, for example, was reported by Biegelsen (Xerox, Palo Alto). Demuth (IBM Yorktown Heights) showed in a poster the advantages of using Fourier transformed images to get at weak signals in the STM images. Stroscio (NIST, Gaithersburg) presented a poster showing the dispersion of evanescent gap states in GaAs, resulting from wavefunction continuity between metal and semiconductor surface regions, using spectroscopic imaging techniques. An exactly similar application of using energy resolved spectroscopic imaging was applied to gap states, but in superconducting systems, in regions of the vortex cores by Hess (AT&T Bell Labs).

METALS

Kuk (AT&T Bell Labs) started off the session on metals with a discussion of the surface band structure of metals and the use of the jellium model to interpret STM images. It was found that some electronic bands such as d-bands are too localized (as predicted by theory) to be observed by tunneling spectroscopy and some bands reveal large dispersion with long decay lengths. The other half of the talk dealt with the study of oxygen chemisorption on Cu(110). He found that O atoms grow at low coverage on terraces as long isolated rows. At coverages >0.2 ML, one begins to see some 1x2 structure; at coverages >0.3 ML, one begins to get a second adsorption site. Ogletree (Lawrence Berkeley Lab) studied the chemisorption of sulfur on Re(0001). The image consists of hexagonal rings of sulfur arranged on a $2\sqrt{3}x2\sqrt{3}$ R30° lattice. The sulfur overlayer was stable even after the tip made contact with the sample. Rousset (Univ. of Paris) studied the adsorption of sulfur on stepped Cu surfaces. She observed two coexisting superstructures of sulfur, namely, p(2x2) and c(4x2). On Cu(1,1,1) sulfur adsorption destabilizes the [011] steps, resulting in step faceting. On Cu(8,1,0), the [001] steps are stable under sulfur adsorption. Frenken (IBM Watson) studied the thermal roughening of Ag, Cu, and Ni (115) surfaces. He used STM to "watch" the metal surface roughen by the proliferation of kinks in step surfaces. This occurred at a roughening temperature $T_r \approx 0.60\ Tm/k_B$.

SUPERCONDUCTORS

In principle, the STM can be a valuable tool in the study of high temperature superconductors, providing information about atomic surface structure and electronic density of states. However, measurements made on polycrystalline samples often reveal properties that are not intrinsic but due to material inhomogeneities or grain boundaries. STM studies on single crystal samples of Bi-Sr-Ca-Cu-O were reported by Nogami (Stanford Univ.) and by Tanaka (Nippon Steel). These two groups concluded that the freshly cleaved surface exposed an insulating Bi-O plane; the atomic positions within this plane were accurately determined. STM images of thin film samples of chemical vapor deposition (CVD) grown Bi-Sr-Ca-Cu-O are also consistent with a surface that is primarily Bi-O. These results help explain the difficulty in establishing contact with the Cu-O planes where the superconductivity is believed to reside.

Kent (Univ. of Geneva) studied thin films of Y-Ba-Cu-O by a related technique called scanning tunneling potentiometry (STP). In this technique the sample topography is measured as in the usual STM. In addition, a dc current is passed through the film, and the local voltage drop is measured during periods when the tip-sample voltage is zero and no tunneling current could otherwise flow. The resulting potential image consists of a series of terraces of approximately constant potential separated by steps where the potential changes abruptly; the terraces can be identified as the superconducting grains and the steps as the insulating barriers that give rise to resistivity and degraded superconducting properties.

The most dramatic use of the STM in the study of superconductivity was reported by Hess (AT&T Bell Labs). He was able to image the magnetic flux lattice in a type II superconductor by differentiating between superconducting regions where an energy gap occurs in the current-voltage characteristic and normal core regions that have no energy gap. The images he obtained were consistent with those obtained by the decoration technique using iron filings. However, he also observed several unexplained phenomena. In particular, at large magnetic fields just less than the upper critical field when the vortices are close together, a sublattice appears to develop with new vortices occupying positions at midpoints in the original fluxoid lattice. This may be a new phenomenon not previously seen by other techniques or predicted by theory, or perhaps merely an artifact due to some peculiarity of the tunneling, such as a multiple tip effect.

SOLID/LIQUID INTERFACES

The STM is beginning to emerge as an important tool for in-situ studies of the solid/liquid interface during electrochemical reactions. Initially, there were problems associated with large Faradaic currents overwhelming the small tunneling current and with deterioration of the tunneling tip by electrochemical reactions. These difficulties have been overcome by coating the tip with a glass or polymer (only the point of the tip is exposed) and by careful control of cell potentials using a reference electrode. Now it is possible to obtain STM images of the changing surface structure of electrodes during electrochemical reactions. Much of the early pioneering work in this field was done by Hansma and coworkers [Univ. of Calif. at Santa Barbara (UCSB)].

Uosaki (Hokkaido Univ.) reported on Cu deposition on Pt and Pd electrodes; these electrodes are polycrystalline and initially rough but become much smoother during plating. Itaya (Tohoku Univ.) has done similar studies using single crystal Pt electrodes. Initially, the flame-annealed Pt electrodes have nearly atomically flat surfaces consisting of large (100-nm-wide) terraces joined by monatomic steps. After potential cycling in a weak acid, bumps appear on the terraces; the dependence on experimental variables is being determined. In addition to studying metal electrodes, Itaya and coworkers are obtaining in-situ STM images of semiconductor electrode surfaces. They have imaged the stable hydrogen-terminated Si surface and are beginning to investigate other semiconductor surfaces in aqueous electrolytes, in particular, GaAs and InP. The initial stages of metal (Pt, Au, Ag) electrodeposition on these semiconductor surfaces are also under investigation by Itaya and coworkers. Similar studies of Ge and GaAs electrode surfaces were reported by Nagahara (Arizona State Univ.). Nagahara and coworkers investigated electrodeposition of Ni on Ge(111), which produced smooth films for thicknesses less than five monolayers; for thicker films island growth dominated. They were also able to deposit small (100 nm) Au dots on p-GaAs under the tunneling tip due to the strong electric fields.

Additional STM studies of metal film electrodeposition were reported by Robinson (Bellcore) and Green (Stanford Univ.). Robinson uses an atomically flat graphite substrate and deposits Ag. The deposition is too rapid to follow in real time, but he obtains STM images during the dissolution process. He sees the removal of the film, one monolayer at a time. Green studies underpotential deposition of Pb on Au(111) and is able to obtain real-time images during deposition and removal. The growth occurs preferentially at step edges on the Au surface. After many repeated complete cycles, the Au substrate becomes roughened.

MACROMOLECULES AND BIOLOGY

One of the most exciting potential applications for proximal probes is in the exploration of macromolecular phenomena, especially biomolecules. The slow growth in this direction, evident over the last several years, began to take on much greater dimensions in Oarai, with 23 different groups reporting results in the form of 13 oral and

25 poster papers. Most of the work focused on STM, but a number of other techniques (force microscopy and ion conductance microscopy) are starting to be used.

The variety of molecules being imaged is large. A number of groups chose to work with highly ordered systems in order to immobilize the molecules and to enhance interpretation prospects. Liquid crystalline materials (Smith, IBM Munich) showed good results in several cases, as did three efforts imaging crystallized electroactive organic salts (Fainchtein, Applied Physics Lab (APL)/ John Hopkins Univ. (JHU); Dai, Academia Sinica, Beijing; and Fujita, Univ. of Tokyo). Several other groups (Möller, Univ. of München; Wilson, IBM Almaden; and Ruan, Academia Sinica, Beijing) imaged phthalocyanine molecules adsorbed on metal/ semiconductor surfaces. Very convincing images of the molecules were presented, with the aromatic rings showing the greatest intensity. Wilson (IBM Almaden) related that the use of a Cu substrate was very important since the phthalocyanine molecules reacted with this surface, thereby pinning the molecule. The biological investigations included work on sickle cell anemia hemoglobin (Smith, IBM Munich); phosphatidylcholine bilayers (Bai, Academia Sinica, Beijing; Vidic, Georgetown Univ.); bacteriophage (Bustamante, Univ. of New Mexico); cytoskeletal microtubules (Hameroff, Univ. of Arizona); collagen (Snellman, Univ. of Turku, Finland); polypeptide (McMaster, Agricultural Force Research Council (AFRC), U.K.); and DNA (Selci, Univ. di Roma; Lindsay, Arizona State Univ.; Besenbacher, Univ. of Aarhus, Denmark; Bustamante, Univ. of New Mexico; Gerber, IBM Zurich). One theme that was repeated several times at the meeting was the absolute need for collaboration between polymer/biology and proximal probe experts. Commercial STM instruments are available, but sample preparation and contrast interpretation are nontrivial.

Progress in macromolecule work has been slowed by the problem of developing analytical tools at the same time as one tries to investigate unknown samples. No equivalent Si(111) 7x7 surface is available as a Rosetta stone to guide the macromolecular studies. Miquel Salmeron (Lawrence Livermore) reviewed known sources of trouble: acceptable flat substrates, molecular immobilization, uncertain contrast mechanisms for "insulating" molecules, identification of observed contrast with molecular features (i.e., identification) and, where appropriate, the need to work in situ (i.e., underwater) to prevent dehydration-induced structural changes. His group has worked very hard to exploit the flat, inert surface of graphite, as have many others; he has now concluded that graphite is inappropriate for several reasons and will begin work on other substrates. A number of other substrates are already being tried, including Au grown epitaxially on mica (Lindsay, Arizona State Univ.) and Au grown on Al (Selci, Univ. di Roma).

Several groups showed evidence that mechanical STM tip/molecule interactions were important. Failure to image molecules on graphite was frequently ascribed to skating the molecule across the flat surface under the impetus of the tip. In one case (Blackford, Dalhousie) direct evidence was shown for physical changes to the molecules by the tip. The Dalhousie group has contributed an important new hopping-imaging technique that may reduce or eliminate the problem. They showed that periodic retraction of the tip while scanning could dramatically improve imaging capability and reduce damage. Another approach to eliminate "molecular skating" is to "glue" the molecule in place.

Successful molecular images on graphite were frequently ascribed to adsorption on edges or grain boundaries. One group investigating DNA denatured the molecule to increase its binding sites; others put down glycerol (Hameroff, Univ. of Arizona) or tri 1-Azcridlyral phosphinoxide (TAPO) (Selci, Univ. di Roma) as glue; still others sought to get an ordered overlayer whereby the molecules were trapped in the overlayer.

In addition to the nanoscopic imaging work, several groups investigated the use of proximal probes to characterize more macroscopic (i.e., 10- to 100-nm) structures. Masai (Mitsubishi) described initial efforts to use the STM as a detection mechanism for immunoassay. Both red (Smith, IBM Munich) and white (Hansma, UCSB) blood cells were imaged, the latter by AFM. Hansma also used AFM to capture a sequence of images showing fibrin, reacting under the influence of thrombin, forming into the fibrinogen chains that constitute blood clots. A video tape of the sequence clearly showed the formation of small segments, their eventual attachment into a filament, and then network formation. Contact forces of $<10^{-8}$ N were essential to acquire this image and, even then, there was evidence for tip-induced molecular displacements. Hansma also demonstrated another proximal probe--the scanning ion conductance microscope--and showed that it could image ion currents through a millipore filter. He is devising ways to improve the technique's lateral resolution (~50 nm) and intends to examine ion channels in biological membranes.

INSTRUMENTS/DEVICES/APPLICATIONS

There were several presentations on instrumentation. Perhaps the most fascinating was Albrecht et al. (Stanford Univ.), who described microfabrication of STMs in silicon. Using standard photolithographic techniques he built up a three-dimensional scanner using ZnO as the piezoelectric actuator. He claimed the advent of the $10 STM was just around the corner. Application areas exist in parallel operation of STMs, reading data storage, lithography, etc.

In the poster session, Grafström (Univ. of Heidelberg) described some laser-assisted STM experiments in which he used the laser light and STM to characterize the thermal response of substrate and probe tip. This year's conference also presented a number of posters in which STM was combined with other types of instruments such as a coaxial impact-collision ion scattering spectrometer (Nomura, NEC Corp.), a room temperature field ion microscope (Sakurai, Univ. of Tokyo), a transmission electron microscope (TEM) operating in the reflection mode (Nagahara, Arizona State Univ.), a molecular beam epitaxy (MBE) apparatus (Deeken, Univ. of Missouri), an optical microscope (Yasutake, Seiko Instruments), and a VG ESCALAB system (Wiesendanger, Univ. of Basel). Several investigators--Watanabe (Toshiba R&D Center), Lang (Stanford Univ.), and Renner (Univ. of Geneva)--presented results on new variable-, low-, or high-temperature STMs. Shimizu (Fujitsu Labs) designed a new inchworm mechanism for ultra high vacuum (UHV) applications; Huerta Garnica (Instituto Polytecnico Nacionale (IPN), Mexico) designed a long range scanner with a range of 40 x 40 square microns; and Fujii (National Research Lab of Metrology, Japan) designed a new STM scanner from an aluminum alloy. Several researchers--Grafström (Univ. of Heidelberg), He (Academia Sinica, Beijing), and Jan (National Taiwan Univ.)--described new computer control and data acquisition systems.

While the principal excitement in proximal probe development has focused on resolving atomic scale surface features, some investigators are now trying to exploit the tunneling tip as a probe to understand device/engineering surface features. In one elegant experiment, the ballistic electron emission microscopy (BEEM) technique [Bell, Jet Propulsion Lab (JPL)/Calif. Inst. of Tech. (CIT)] was used to show that an AlAs layer capping GaAs was sufficient to prevent hypothesized interdiffusion of Au-Ga and to form a nearly defect free Schottky barrier. The band structure of AlAs was shown not to appear until three monolayers had been deposited. Others examined the potential behavior of pn devices from a cross section (Kordic, Philips Research, Netherlands) and the surface stability of H-passivated silicon (Niwa, Matsushita Electric Ind. Co.). The behavior of field emission cathodes is known to suffer from particulate effects; Niederman (Univ. of Geneva) showed that a tunneling tip could identify specific sites and their emission characteristics. Finally, Smith (IBM Munich) showed that a tunneling tip, used as a displacement sensitive transducer, may improve gravitational wave detection technology by a couple of orders of magnitude. This latter point reinforces earlier work of Colton (Naval Research Lab (NRL), magnetic field detection), Kaiser (JPL/CIT, accelerometer), Quate (Stanford Univ., accelerometer), and Bocho (Rochester, transducer theory) that the tunneling tip may play a major role in detectors.

The very sharp tip of an STM, when operated at higher voltages (10 to 1,000 V) in the field emission regime, can serve as a coherent source of collimated electrons. Saenz (IBM Zurich and Univ. of Madrid) reported on quantum mechanical calculations of these electron beam characteristics. He modeled the source as an array of emitters feeding an electron waveguide followed by a triangular barrier. He found that the angular spread of the emergent beam was independent of the waveguide diameter for most tip geometries. The angular spread is instead determined by the barrier characteristics and is typically 10° to 15° full width. The only exception is for the teton geometry where the predicted angular spread is about one-half as large.

These field emission sources have been used to excellent advantage in electron holography as reported by Tonomura (Hitachi). Electron holography is similar to conventional optical holography except that the hologram is produced by the interference of two electron beams; the reconstruction is by optical techniques. Tonomura previously had used this technique to demonstrate the existence of the Aharonov-Bohm effect. He reported some new results relating to magnetic vortices in type II superconductors. In this recent experiment an electron beam passes by the edge of a superconductor and is deviated by the magnetic field pattern associated with the flux lattice. Reconstruction of the resultant hologram provides an image with sufficient resolution to see individual fluxoids.

FORCE MICROSCOPY (AND OTHER PROXIMAL PROBES)

There was a small session on force microscopy highlighted by the invited talk on "Scanning Probe Microscopy" by Wickramasinghe (IBM Watson), who talked about the current status and future trends in this area, which goes back three decades. After a brief review of the history behind the development of the scanned probe microscopes, he discussed recent developments in the areas of scanning tunneling microscopy, magnetic force microscopy (MFM) (where he has achieved a resolution of 25 nm using Ni tips), electrostatic force microscopy (which was used to measure the voltage gradient between a pn junction), near-field thermal microscopy that uses a microthermal couple as a tip, and near-field acoustic microscopy that uses an acoustic transducer instead of an optical pump to excite an absorber. In the poster session, Williams (IBM Watson) described a capacitive microscope used to image the dopant density in Si. The device has a spatial resolution of 25 nm and is capable of measuring capacitance variations of 10^{21} F/$\sqrt{Hz}$. Pohl (IBM Zurich) discussed many possible extensions of the STM technique to measure fields, photons, and forces. He was able to use force measurements to distinguish between clean and adsorbate covered surfaces, to perform local optical spectroscopy with unprecedented resolution, and to trace out the borders of semiconductor junctions. Wickramasinghe's talk was complemented by the invited talk given by Hansma (UCSB) in the session on liquid/solid interfaces. Hansma focused on imaging liquid-solid interfaces such as electrodes and biological molecules with scanning probe microscopes. (The designs of the scanning probe microscopes were discussed in a separate poster paper by Drake of UCSB.)

There were two other talks and several posters given on various aspects of force microscopy. Terris (IBM Almaden) talked about charge imaging and contact charging (tribocharging) using a force microscope. He developed a method to image localized charge on insulating surfaces in which charge and topography can be distinguished and the sign of the charge determined. The method uses an oscillating tip and an electrode behind the sample to measure the force gradient. By touching a Ni tip to the surface of polymethyl methyl methacrylate (PMMA), he recorded the first observation of bipolar charge transfer in a single tribocharging event. Colton (NRL) presented a poster on measuring the nanomechanical properties--elasticity and hardness--by using the AFM as a nanoindenter. He also was able to measure the surface forces--both attractive and adhesive forces--associated with various surfaces, including monolayer films deposited on metal surfaces. Baratoff (IBM Zurich) presented a poster on the atomic scale electronic and mechanical interaction effects in STM and AFM. Baratoff's group used ab-initio calculations to correlate atomic scale tip-sample forces with tip-induced changes in electronic structure for graphite(001) and Al(111) surfaces. Nagahara (Arizona State Univ.) investigated the effects of strain caused by tunneling. He found that reversible elastic strain accompanies tunneling (without plastic flow) for a W tip on InP. The tunneling gap size and tip shape could be observed directly during tunneling. The strain was measured with a TEM through the electron beam Bragg diffraction contrast mechanism. Uozumi

(Aoyama Gakuin Univ.) detected mechanical contact of the tip to the surface by an ultrasonic pulse-echo method. Grütter (Univ. of Basel) talked about high resolution MFM of periodic and nonperiodic magnetic structures. The resolution was found to be tip and sample dependent. A resolution as high as 10 nm was found for FeNdB. Hartman (KFA-Jülich) presented a theory of MFM that analyzed the mechanisms responsible for contrast formation in MFM.

Most of the other posters focused on the design of new AFMs or their application. For example, Albrecht (Stanford Univ.) presented a poster on the microfabrication of thin film SiO_2 and Si_3N_4 cantilevers with integrated tips for AFM. Erlandsson (Univ. of Linköping) built a long scan range AFM that uses a fiber-based laser interferometer as the force sensor. Alvarado (IBM Zurich) developed an MFM using a polarizing interferometer to measure the deflection of GaAs or Si cantilevers with a small ferromagnetic tip attached; lateral resolution down to 30 nm was measured. Sarid (Univ. of Arizona) used a laser diode to illuminate a vibrating tip as a way to measure force gradients. Göddenhenrich (KFA-Jülich) built an AFM using capacitive displacement detection. Schmidt (Johann Wolfgang Goethe Univ.) constructed cantilever force sensors from carbon and glass fibers. Ishizaka (Tohoku Univ.) imaged the surfaces of metal oxides in air with the AFM. Barrett (Stanford Univ.) used an optical deflection-sensed AFM that also uses microfabricated cantilevers to examine atomic steps of a polished sapphire surface. He was also able to image the accumulation of charge on surfaces (with the same periodicity as the step) by applying a bias to the back side of the sample. Yamada (National Research Lab of Metrology, Japan) studied layered compounds--BN and mica; Heinzelmann (Univ. of Basel) used AFM to study thin films of hydrogenated amorphous carbon coating on magnetic recording media and AgBr single crystals; and Bryant (Univ. of Missouri) imaged purple membranes. Wadas (Univ. of Basel) analyzed magnetic bit patterns taking into account the magnetic and van der Waals interactions between the tip and sample. Iizuka (Alps Electric Co.) built a combined MFM and scanning electron microscope (SEM) in order to resolve important questions concerning the relationship between measured force and domain distribution and the influence of stray fields associated with the tip.

LITHOGRAPHY

There were six posters and one talk dedicated to patterning with the STM. However, several other presentations showed patterning results unrelated to their main topic. Alex deLozanne (Univ. of Texas) gave the talk and devoted part of it to an overview of patterning efforts with the STM both at STM '89 and in the literature. Various techniques were described. Several people reported e-beam drilling 3-nm holes into graphite (e.g., Albrecht et al., Stanford Univ.; Rabe et al., Max-Planck, FRG; Thomson et al., Manitoba Univ., Canada). This works in air and it appears that water vapor is the critical atmospheric ingredient. Dijkkamp et al. (Philips Research, Netherlands) created somewhat larger features in silicon by crashing the tip mechanically into a silicon surface. Surprisingly this seemed a repeatable process! Marrian (NRL) presented the only results on lithography with an actual resist and went rather further than others by quantifying exposure thresholds, resolution limits, and energy dependence of the feature size. At the University of Texas, deLozanne has deposited features from organo-metallics and WF_6. Feature sizes down to 10 nm and a threshold of 15 V were claimed. Interestingly with WF_6, both etching and deposition were observed on Si<111>. The determining factor seemed to be the sample temperature, 50 °C being the threshold. Similar results have been reported in the literature by McCord et al. (IBM Yorktown Heights). One would expect that this is an area where interest will grow in the future.

Several presentations on silicon had relevance to microfabrication in that they studied the oxidation of silicon following various oxide stripping and surface passivation steps. Some impressive passivation times were claimed of up to 60 hours in air (Niwa, Matsushita, Japan). Nakagawa (Toray R.C., Japan) observed atomic resolution in air for several hours. However, most authors acknowledged that oxidation rates and resolution degradation increased significantly under the action of the tunnel current.

SUMMARY

It is clear that the STM is becoming an accepted surface analysis instrument. Results, particularly in the semiconductor field, were presented that displayed short range atomic order not visible with other surface analytical techniques. In fact, some of these studies belonged in a mainstream surface physics conference. On the other hand, there was a tremendous amount of work presented that consisted of attempts (usually only partially successful) to image a complex material or system. In only a very few cases outside the semiconductor area (D. Smith, IBM Munich, for example) were the STM results of sufficient quality to be analyzed to provide insights into the fundamental physics, chemistry, or biology of the system being studied. Nevertheless, clear progress was evident in these important efforts to broaden the scope of proximal probe impact.

The proceedings of this conference are to be published in the *Journal of Vacuum Science and Technology* early in 1990.

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Richard J. Colton is a supervisory research chemist and head of the Advanced Surface Spectroscopy Section at NRL. He earned his B.S. and Ph.D. degrees from the University of Pittsburgh in 1972 and 1976, respectively. He performed his graduate work under the direction of Professor J.W. Rabalais in the areas of ultraviolet and x-ray photoelectron spectroscopy. In 1976, he was awarded a National Research Council Resident Research Associateship at NRL for a research proposal dealing with secondary ion mass spectrometry (SIMS). Dr. Colton joined the staff at NRL in 1977 and conducts basic and applied research in the area of surface chemistry. His research interests include surface and materials analysis by electron spectroscopy and SIMS, the development of new surface analytical techniques, the study of the mechanisms of molecular and polyatomic ion emission and, most recently, the study of surfaces and molecular adsorbates by scanning tunneling microscopy, the measurement of the nanomechanical and surface forces properties of materials using atomic force microscopy, and the development of new sensor concepts using electron tunneling. Dr. Colton is a member of the ACS, ASTM, Sigma Xi, and AVS. He is first vice chairman of the ASTM E-42 Committee on Surface Analysis and was a former chairman of the AVS Applied Surface Science Division. Dr. Colton is also a member of the editorial boards of Surface and Interface Analysis and Applied Surface Science.

C.R.K. Marrian received a B.A. degree in engineering and a Ph.D. degree in electrical engineering in 1973 and 1978, respectively, from Cambridge University, England. He subsequently spent nearly 3 years at C.E.R.N. in Switzerland working on a detector for a quark search experiment. In 1980 Dr. Marrian joined the Surface Physics Branch at NRL. At NRL he has continued his studies of high current density thermionic emitters, particularly under conditions of nonideal vacuum. More recently he has developed research interests in the limits of lithographic techniques in the field of microfabrication. To this end he has used the low energy electron beam available in an STM-type configuration to study the electron-material interactions in e-beam lithography. Dr. Marrian is further involved in research into architectures and algorithms for electronic implementations of artificial neural networks.

James S. Murday received a B.S. in physics from Case Western Reserve in 1964 and a Ph.D. in solid state physics from Cornell University in 1970. He is superintendent of the Chemistry Division at NRL and advisor to the Surface/Interface Physics Program at ONR. His research interests include interface analysis; surface modification technology; surface reaction kinetics; chemistry of electronics materials; and application of surface science to contamination control, corrosion, tribology, and chemical microsensors. Dr. Murday is a member of the APS, ACS, AVS, and MRS. In the AVS he has served as chairman of the Local Arrangements Committee for the 1982 and 1986 National Symposia, trustee for 1981-1984, director for 1986-1988, and member of the AIP Governing Board for 1986-1989.

Joseph A. Stroscio is a research chemist at NIST. He earned a B.S. (highest distinction) in physics from the University of Rhode Island in 1978 and a Ph.D. in physics from Cornell University in 1986. He performed his graduate research work under the direction of Professor W. Ho in the area of surface physics. In 1985, he was awarded a Postdoctoral Research Associateship at the IBM T.J. Watson Research Center, where he performed research in scanning tunneling microscopy. His research interests include interface analysis, surface modification technology, and the development of new surface analytical techniques. Dr. Stroscio is a member of AAAS, APS, AVS, and MRS.